A Classification Scheme for FACTS Controllers

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Abstract

There currently exists no formal classification scheme for flexible alternating-current transmission systems (FACTS) controllers, and the paper aims to remedy this. The proposed classification is based on five characteristics of the controllers: connection, commutation, switching frequency, energy storage and presence of a dc port. There are 180 combinations. Six examples are examined, and all the main existing FACTS controllers are tabulated and classified.

I. Introduction

Flexible alternating-current transmission systems (FACTS) are defined by the IEEE as “ac transmission systems incorporating power electronics-based and other static controllers to enhance controllability and increase power transfer capability” [1]. Similarly, a FACTS controller is defined as “a power electronics-based system or other static equipment that provides control of one or more ac transmission parameters”. In recent years, many different FACTS controllers have been proposed, performing a wide variety of functions. Review papers have surveyed them, the IEEE has listed definitions of them, but to date no classification scheme has been proposed.

There are several reasons why this situation is unsatisfactory, from both academic and practical viewpoints. It would be advantageous to organise the existing FACTS controllers into family groups, rather than regarding them as a collection of disparate items. This would help newcomers to the field to recognise relationships between the various controllers, and to appreciate their similarities and differences. It could aid in the understanding of their operation and characteristics. It would also enable researchers to identify “missing” controllers that have not yet been proposed and develop them.

An ideal classification scheme would have these properties: it would be *simple* to apply and understand; it would be *objective and quantitative*; it would be *unambiguous and clear*; it would be *useful* to those interested in the field; and, finally, it would be *extendible*, to cope with further advances in the field of FACTS. In this paper, we propose a scheme which we believe goes a considerable way towards meeting these goals.

Our proposed classification scheme is multi-dimensional, in that it classifies FACTS controllers according to five independent measures, which may be considered as five orthogonal axes. A drawback with any multi-dimensional classification scheme is that certain combinations of characteristics may be impossible or impractical, resulting in gaps. For example, the combination of “high frequency switching” and “natural commutation” is inapplicable, because fast SCRs are not currently available. This is a practical limitation, which might change with the introduction of yet unforeseen devices. A positive aspect of these “missing combinations” is that they can stimulate new ideas which might be developed to improve power system operation. Therefore, we believe our classification scheme for FACTS controllers has value not only in organising existing technology into a coherent body of knowledge, but also in providing a starting point for researchers who wish to develop new techniques.

II. Classification Scheme

In our proposal, FACTS controllers are classified by considering five independent characteristics: 1) connection; 2) commutation; 3) switching frequency; 4) energy storage; and 5) dc port. Examination of each characteristic of a particular FACTS controller results in a symbol S_1 to S_5. The five symbols are then concatenated (with hyphen separators) to form a classification string of the form S_1-S_2-S_3-S_4-S_5. For example, the static VAR compensator's classification string is **1P-NC-LF-ZES-NDC**. In the following subsections each of these five characteristics is defined and explained.

A. Connection

FACTS controllers modify the series and parallel impedances of transmission lines. The way a FACTS controller is connected to the ac power system has a direct effect on the transfer of active and reactive power within the system. Series connected controllers are usually employed in active power control and to improve the transient stability of power systems. Shunt connected controllers govern reactive power and improve the dynamic stability.

The IEEE groups FACTS controllers into three main categories based on how they are connected to the ac power system: series, shunt, and combined series-and-shunt [1]. We follow this, but we first divide them into one-port and two-port connections, then subdivide the one-ports into series and parallel (shunt) connections. (When counting the number of ports, only the ac ports are considered: dc ports for energy storage elements such as batteries are considered separately.)

Connection = one-port, series (**1S**); *one-port, parallel* (**1P**); *or two-port* (**2**)

One of these three is chosen as the first symbol (S_1) of the five-part classification string.

B. Commutation

Commutation is a major characteristic of the semiconductor switching devices employed in FACTS controllers. Commutation can either be *forced* as with GTOs, or *natural* as with SCRs, which turn off at zero current. (There are, of course, ways of forcing an SCR to turn off at non-zero current. For example, an auxiliary device can be employed to force the current in the main SCR to zero. We classify this case as **FC**, because in operation a non-zero current can be turned off at an arbitrary time.)

Commutation = forced commutation (**FC**); *or natural commutation* (**NC**)

For **NC** the number of commutations during a synchronous frequency cycle is fixed, whereas for **FC** it is variable at will. One of these is chosen as the second symbol (S_2) of the classification string.

C. Switching Frequency

Power systems have a synchronous frequency of 50 or 60 Hz, whereas power electronics based systems can operate over a wide range of switching frequencies. The choice of switching frequency affects the level of harmonics that controller introduces into the power system: a higher frequency allows lower harmonic levels. It also has an effect on the devices' switching loss: the higher the frequency, the greater the loss. A tradeoff must be made.

With natural commutation, the switching frequency of each device is generally "low", equal to the system's synchronous frequency of 50/60Hz. Alternatively, to improve harmonic performance, the switching waveforms may be notched or otherwise modified. We call this "medium" switching frequency: a few times the synchronous frequency. Finally, "high" frequency switching may be used, typically using pulse-width modulation with a carrier frequency many times the mains frequency.

To put some numbers to this, "low" can be considered as frequencies up to and including the 50/60Hz mains frequency. We suggest that "medium" should refer to switching frequencies f_s between one and ten times the synchronous frequency f (e.g. 100–500Hz for a 50Hz system). Frequencies higher than this are classified as “high”. The upper limit of operation is set by the device characteristics. GTOs are currently the device of choice in power system applications. They are less expensive than other types and have higher blocking voltages and forward currents. They can turn on in typically 5–10μs and turn off in about 10–30μs. This leads to a recommended switching frequency of about 3kHz, with an upper limit of perhaps 5kHz imposed by excessive switching loss [23].

Switching frequency = low, $0 < f_s \leq f$ (**LF**); *medium $f < f_s \leq 10f$* (**MF**); *or high, $f_s > 10f$* (**HF**)

LF, **MF** or **HF** is used as the third symbol (S_3) of the classification string.

D. Energy Storage

In certain controllers, particularly those that must absorb and deliver active power, substantial energy storage is needed. By substantial, we mean enough to deliver active power to the power system over an interval of a few seconds or more. In some other controllers, reactive power is generated and the only active power is that associated with parasitic losses. Energy storage elements have to be able to provide transient overload capability for several cycles. Energy storage at time scales comparable to a mains cycle is excluded from consideration as insignificant.

Energy storage = zero energy storage (**ZES**); *capacitor energy storage* (**CES**); *battery energy storage (***BES***); superconducting energy storage* (**SES**); *or external energy source* (**EES**)

To clarify these terms, let us start by defining a dimensionless number

$$N = \frac{Ef}{S} \tag{1}$$

where E is the available energy stored within the controller, S is its rated apparent power and f is the synchronous frequency. The aim is to get a feel for the time scale of the various energy storage categories. A physical interpretation is that N is the number of mains cycles it would take for the energy E to be delivered at a power equal to S. For example, if equipment installed in a 50Hz system is rated at 100MVA and stores 25MJ of energy, but cannot discharge further than 15MJ, we find the available energy E = 10MJ and N = 5 cycles.

Zero energy storage, ZES, strictly applies to controllers that have no energy storage elements, such as the thyristor controlled braking resistor (TCBR). But we also extend this category to include controllers having inductors or capacitors in the ac side. This is because the time scale for delivering the stored energy is very small. For instance, consider the static VAR compensator (SVC). The peak stored energy in a three-phase SVC operating in capacitive mode is $E = CV^2$, where C is the equivalent SVC capacitance and V is the line voltage. The three-phase apparent power is $S = 2\pi fCV^2$. Equation (1) gives N = 0.16 cycle. In this context, the SVC stores an insignificant amount of energy.

Capacitive energy storage, CES, refers to controllers that use capacitors on the dc side for energy storage and which are capable of supplying a transient overload for several cycles. As an example, let us consider a hypothetical FACTS controller in a 60Hz power system. In addition to its rated 100MVAr reactive power capability, under transient conditions this equipment must supply 125MW of active power for 10 cycles. To achieve this, the energy stored in the dc capacitor bank must be at least 125MW × 10 / 60Hz = 20.8MJ. Suppose the dc capacitor voltage is nominally 6kV. Then $E = ½CV^2$ gives the minimum capacitance as C = 1.16F. In practice C must be larger, because the dc voltage should be kept close to its nominal value for the power converter to work properly. Let the voltage fall to 5kV at the end of the transient. The capacitance must now be 3.78F, corresponding to a maximum stored energy of 68.07MJ and a minimum of 47.25MJ . For this case, (1) gives N = (68.07 – 47.25)MJ × 60Hz / 100MVA = 10 cycles.

With battery energy storage, BES, electrochemical batteries can be used to supply active power at peak times. The time scale is much greater than CES and ZES, around an hour. Therefore $N \approx 2 \times 10^5$ cycles. (Since a battery's voltage remains substantially constant throughout its discharge, the unavailable capacity is small, unlike CES.)

Superconducting energy storage, SES, is an alternative method of injecting and absorbing active power. Once the superconducting magnet is in its storage phase, it can steadily supply or absorb energy. Therefore its capability is considered similar to that of BES.

There are many possibilities for an external energy source, EES. They include conventional turbine-driven generators, which derive their thermal energy from fossil fuels or nuclear fission, as well as hydroelectric, photovoltaic, wind and wave generators. Assuming an inexhaustible external source of energy, $N = \infty$.

Fig. 1 shows the regions that can be considered as ZES, CES, BES/SES and EES in terms of N. The boundaries are indicative rather than prescriptive. The fourth symbol (S_4) of the classification string is **ZES**, **CES**, **BES**, **SES** or **EES**.

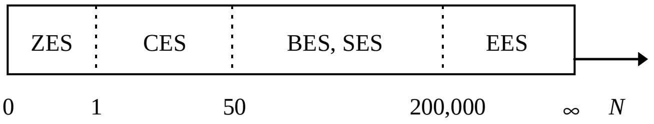


Fig. 1: Number of cycles of stored energy typical of ZES, CES, BES, SES and EES.

E. DC Port

The current FACTS controllers can also be divided into two groups according to the presence or absence of a dc port. In the first group, those with no dc port, the components are subjected to alternating voltages and currents only. This group generally employs physical impedance (usually inductors or capacitors) together with back-to-back thyristors. Examples include the SVC and the TCSC. The second group, more recently developed, is those that include one or more ac/dc converters between the ac power system and a dc port. Examples are the SSC and the SSSC. Often no physical impedance is interposed between the ac port and the converter, the leakage inductance of the ac port's step-down transformer providing sufficient reactance. The ac/dc converter is controlled in such a way that the desired ac port characteristics are produced.

Dc port = dc port employed (**DC**); *or no dc port employed* (**NDC**)

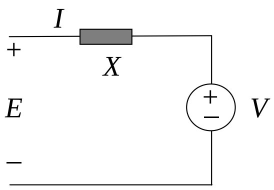


Fig. 2: General schematic model of advanced FACTS devices.

To clarify the discussion, let us consider the general schematic model of Fig. 2. E is the power system's voltage phasor referred to the transformer secondary. The first group of controllers has a physical impedance for X, and $V = 0$. For the second group, X is the leakage reactance of the step-down transformer (referred to the secondary), and V is the fundamental voltage phasor of the ac/dc converter. The effective impedance presented to the power system is

$$Z = \frac{E}{I} = \frac{jX}{1 - A} \qquad (2)$$

where $A = V/E$ is the voltage gain from the power system to the converter. For purely reactive power, $\angle A$ is set to 0. If $A < 1$, Z is inductive; if $A > 1$, it is capacitive. The reactive power produced by the FACTS controller is given by

$$Q = \frac{|E|^2(1-A)}{X} \tag{3}$$

In operation, Q is changed by varying A. The sensitivity $\partial Q / \partial A = -|E|^2 / X$ is inversely proportional to X, so if X is small (e.g. transformer leakage reactance), only a small change in A is needed to move Q over its rated range. An advantage resulting from this is that the magnitude of V is always close to that of E, so the dc port voltages can be relatively low, somewhat in excess of $\pm\sqrt{2}|E|$. A practical disadvantage of small X is that fault currents can be very large, in the order of E/X. Another drawback is that the converter can inject large high-frequency harmonic currents into the power system: even at the switching frequency, the reactance is still quite small.

We recently proposed a new FACTS controller, the Bootstrap Variable Inductance [25]–[27], which includes an ac/dc converter but also a large physical inductance for X. The fault currents and high-frequency harmonics are therefore much lower, giving good power system compatibility. On the other hand, because $0 \le A \le 2$ in our designs, it needs a dc voltage in the order of $\pm 2\sqrt{2}|E|$.

The final symbol (S_5) of the classification string is either **DC** or **NDC**. If the FACTS controller employs energy storage in a dc capacitor, a battery or a superconducting magnet, **DC** is obligatory.

III. Classification Examples

In principle, the proposed scheme allows 180 distinct classifications; in practice the number will be smaller, as certain combinations of characteristics are unlikely or impossible (e.g. **CES** with **NDC**). Here we examine and classify six FACTS controllers. These examples have been chosen to cover the main applications and different approaches. Examples A and B are one-port shunt controllers, B and C are one-port series controllers, while D and E are two-port controllers. Many further examples are given in Tables I, II and III, which detail all the main FACTS controllers.

A. Static VAR Compensator (SVC)

The conventional static VAR compensator consists of a capacitor in parallel with a thyristor-controlled reactor (Fig. 2). It is conventionally used to stabilise a busbar voltage and improve damping of the dynamic oscillation of power systems [2], [3]. Many SVCs have been deployed since 1970.

The SVC has a single port with a parallel connection to the power system, so the first symbol in its classification string is S_1 = **1P**. The thyristors are naturally commutated, so S_2 = **NC**. They switch at the mains frequency, so S_3 = **LF**. As shown above, there is insignificant energy storage and S_4 = **ZES**. Finally, the SVC has no dc port: S_5 = **NDC**. Therefore its classification under this scheme is:

Static VAR Compensator: **1P-NC-LF-ZES-NDC**

B. Static Synchronous Compensator (SSC)

The SSC comprises a voltage source inverter which is connected to power system through a transformer (Fig. 4). Corresponding to Fig. 2, the SSC can draw either capacitive or inductive current [10].

Excluding the dc port, the SSC is a one-port circuit shunted across a busbar (S_1 = **1P**); it uses forced commutation (S_2 = **FC**); its switching frequency is high (S_3 = **HF**); its energy storage element is a dc capacitor (S_4 = **CES**); and this implies a dc port (S_5 = **DC**).

Static Synchronous Compensator: **1P-FC-HF-CES-DC**

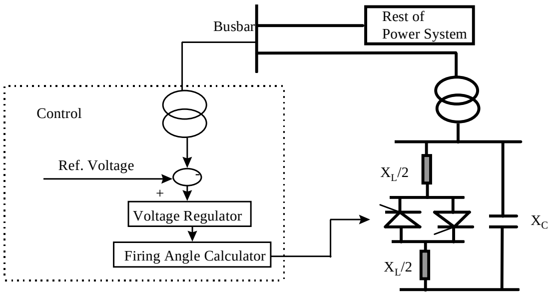


Fig. 3: Static VAR Compensator.

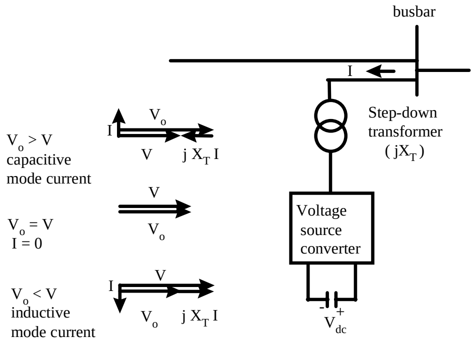


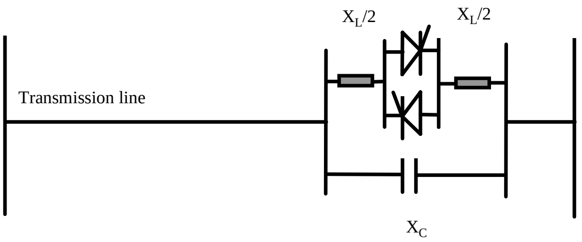
Fig. 4: Static Synchronous Compensator.

C. Thyristor Controlled Series Capacitor (TCSC)

The TCSC consists of a series capacitor bank, shunted by a Thyristor Controlled Reactor to provide a smoothly variable series capacitive reactance [1]. Fig. 4 shows a TCSC in series with a transmission line. It injects a series voltage proportional to the line current but in quadrature with it. Inserting a TCSC modifies the equivalent reactance of the line, and the active power flow can be varied [15].

The TCSC is a one-port circuit in series with a transmission line; it uses natural commutation; its switching frequency is low; it contains insignificant energy storage elements; and it has no dc port.

Thyristor Controlled Series Capacitor: **1S-NC-LF-ZES-NDC**



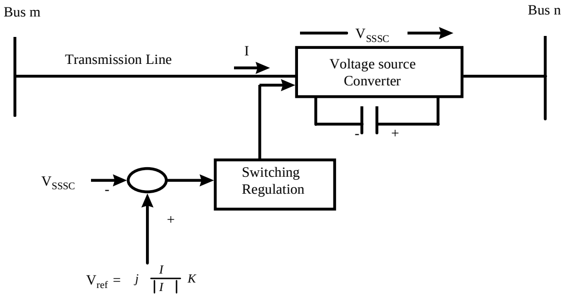


Fig. 5: Thyristor Controlled Series Capacitor.

Fig. 6: Static Synchronous Series Compensator.

D. Static Synchronous Series Compensator (SSSC)

The SSSC is a static, synchronous generator operated as a series compensator. Its output voltage is in quadrature with the line current, and is controllable independently of it [17]. Its purpose is to increase or decrease the overall reactive voltage drop across the line and thereby control the transmitted power. Fig. 6 shows the SSSC model. It employs a step-down transformer, whose leakage inductance forms the reactance in series with an ac/dc converter.

The SSSC is a one-port circuit in series with a transmission line; it uses forced commutation; its switching frequency is high; its energy storage element is a capacitor; and it has a dc port.

Static Synchronous Series Compensator: **1S-FC-HF-CES-DC**

E. Interphase Power Controller (IPC)

The IPC is a series controller of active and reactive power. It consists of inductive and capacitive branches subjected to separately phase-shifted voltages. The active and reactive power can be set independently by adjusting the phase shifters and/or branch impedances, using mechanical or electronic switches [1]. The IPC can regulate both the direction and the amount of active power transmitted through a transmission line [18].

The IPC is a two-port circuit (in series with a transmission line and in parallel with a busbar); it uses natural commutation; its switching frequency is low; it has insignificant energy storage; and it has no dc port.

Interphase Power Controller: **2-NC-LF-ZES-NDC**

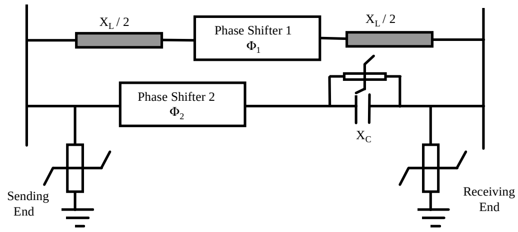


Fig. 7: Interphase Power Controller.

F. Unified Power Flow Controller (UPFC)

The UPFC (Fig. 8) is a combination of an SSC and an SSSC, sharing a common dc link. The UPFC can control both the active and reactive power flow in the line. It can also provide independently controllable shunt reactive compensation [1]. In other words, the UPFC can provide simultaneous control of all the basic transmission line parameters.

The UPFC is a two-port circuit (in series with a transmission line and parallel with a busbar); it uses forced commutation; its switching frequency is high; it has capacitive energy storage; and it employs a dc port.

Unified Power Flow Controller: **2-FC-HF-CES-DC**

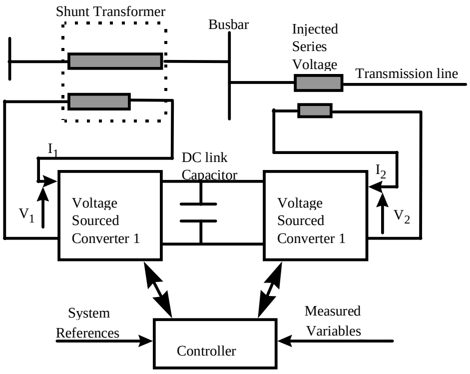


Fig. 8: Unified Power Flow Controller.

IV. Discussion

Within this classification scheme, two major groups of FACTS controllers can be recognised. First, there are conventional controllers which have insignificant energy storage and use SCR thyristors as their switches. These commutate naturally at the mains frequency, adjusting the effective value of a passive capacitive/inductive reactance by varying the firing angle of the thyristors. This family can be classified as

S_1-**NC-LF-ZES-NDC**.....with $S_1 \in \{\mathbf{1P}, \mathbf{1S}, \mathbf{2}\}$

Second, more advanced FACTS controllers utilise high-frequency switching with forced commutation, typically using GTOs, and have a dc port. The circuits contain only small inductances. Closed-loop control is applied to produce the desired currents or voltages at the terminals. They can be classified as

$$S_1\text{-}\mathbf{FC}\text{-}\mathbf{HF}\text{-}S_4\text{-}\mathbf{DC}: \quad \text{with} \quad S_1 \in \{\mathbf{1P}, \mathbf{1S}, \mathbf{2}\} \quad \text{and} \quad S_4 \in \{\mathbf{CES}, \mathbf{BES}, \mathbf{SES}, \mathbf{EES}\}$$

V. Conclusion

All existing FACTS controllers may be classified according to the proposed scheme, which currently allows 180 possibilities (including all possible and impossible cases). It is extendible in future by adding further choices to the existing categories, and by adding new characteristics if these should become relevant. We hope that this proposal will be adopted (perhaps adapted!) as the basis of a universal classification scheme for FACTS controllers.

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Table I: Shunt Connected FACTS Controllers

Name	Classification	Main Function	Subsidiary Functions
BESS Battery energy storage system	**1P-FC-HF-BES-DC**	Load Levelling	Voltage stabiliser, active filter, UPS
SSC Static synchronous compensator	**1P-FC-HF-CES-DC**	Voltage control	VAR compensation, damping of oscillation, transient stability
SSG Static synchronous generator	**1P-FC-MF-EES-DC**	Exchanging independently controllable real and reactive power with power system.	
SVC Static VAR compensator	**1P-NC-LF-ZES-NDC**	Voltage control	VAR compensation, steady state and dynamic stability
SVG Static VAR generator	**1P-NC-LF-ZES-NDC**	Generating or absorbing reactive power	Steady state and dynamic stability (TCR and TSC in parallel)
SVS Static VAR systems	**1P-NC-LF-ZES-NDC**	Stability limit extender at the midpoint of a long transmission line.	Voltage control
SMES Superconducting magnetic energy storage	**1P-FC-HF-SES-DC**	Dynamical control of power flow in ac system	As SSC, the energy storage is superconducting reactor
TCBR Thyristor controlled braking resistor	**1P-NC-LF-ZES-NDC**	Aiding to damp power flow oscillation and decrease risk of losing synchronism	
TCR Thyristor controlled resistor	**1P-NC-LF-ZES-NDC**	Continuous reactive power absorber	
TSC Thyristor switched capacitor	**1P-NC-LF-ZES-NDC**	Stepwise reactive power generator	
TSR Thyristor switched reactor	**1P-NC-LF-ZES-NDC**	Stepwise reactive power absorber	
BVI (parallel connected) bootstrap variable inductance	**1P-FC-HF-CES-NDC**	Voltage stabiliser and/or load power factor corrector	

Table II: Series Connected FACTS Controllers

Name	Classification	Main Function	Subsidiary Functions
SSSC Static synchronous series compensator	**1S-FC-HF-CES-DC**	Controlling transmitted electric power by increasing or decreasing reactive voltage drop while expecting no SSR effect	Increase or decrease resistive voltage drop across the transmission line to enhance dynamic behaviour
TCSC Thyristor controlled series capacitor	**1S-NC-LF-ZES-NDC**	Capacitive reactance compensator in a continuous manner	
TCSC′ Thyristor controlled series compensator	**1S-NC-LF-ZES-NDC**	Capacitive/inductive reactance compensator in a continuous manner	
TCSR Thyristor controlled series reactor	**1S-NC-LF-ZES-NDC**	Inductive reactance compensator in a continuous manner	
TSSC Thyristor switched series capacitor	**1S-NC-LF-ZES-NDC**	Capacitive reactance compensator in a stepwise manner	
TSSC′ Thyristor switched series compensation	**1S-NC-LF-ZES-NDC**	Capacitive/inductive reactance compensator in a stepwise manner	
TSSR Thyristor switched series reactor	**1S-NC-LF-ZES-NDC**	Inductive reactance compensator in a stepwise manner	
BVI (series connected) bootstrap Variable Inductance	**1S-FC-HF-CES-NDC**	Capacitive/inductive reactance compensator without SSR	Transient stability improvement, fault current limiter

Table III: Two-Port FACTS Controllers

Name	Classification	Main Function	Subsidiary Functions
IPC Interphase power controller	**2-NC-LF-ZES-NDC**	Independent active and reactive power controller	
TCPST Thyristor controlled phase shift transformer	**2-NC-LF-ZES-DC**	Controlling power flow distribution and providing high speed variable phase angle to control power system transient and dynamic stability	
UPFC Unified power flow controller	**2-FC-HF-CES-DC**	Terminal voltage control, phase angle regulation, series line compensation	VAR compensation